Jet Propulsion Laboratory
California Institute of Technology

JPL GNSS Receivers, Past, Present, and Future

SCAN workshop

Larry Young

Jet Propulsion Laboratory, California Institute of Technology

Feb 16, 2017

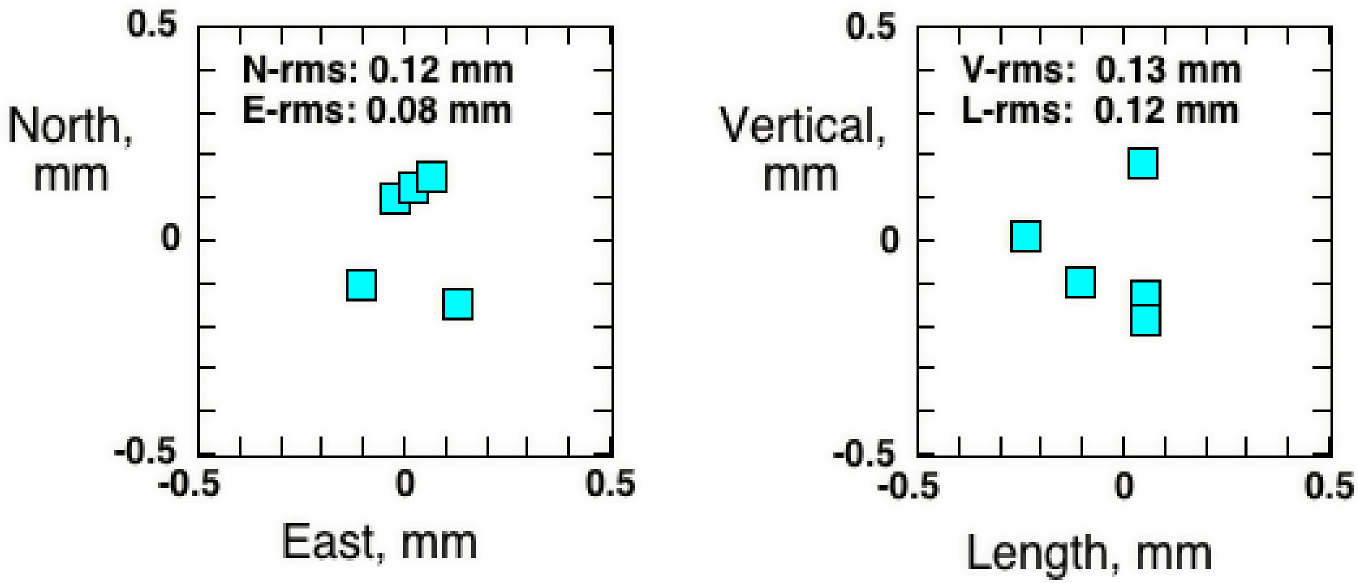
Copyright 2017 California Institute of Technology. U.S. Government sponsorship acknowledged.

JPL's GNSS Receiver Goals

- Accuracy/Precision
  - GPS has 0.1 mm precision. Why not use it?
- Autonomy
  - 32 of our instruments launched into space, all came alive with no ephemeris data, acquired GNSS signals, solved for PVT, and began science collection with only command consisting of POWER ON
- Flexibility
  - all instruments software and firmware reprogrammable in orbit
- Capability
  - GPS + new signals + new constellations + star camera + digital beam steering + single-antenna attitude estimation + inter-spacecraft range and bearing + telemetry transfer

Precision

- Limiting-Performance test results
  - 29-m baseline measured on JPL mesa



- Repeatability over 5 successive days is 0.1 mm (0.7 arc sec

GPS Precision (backup)

- GPS spreads ~20 W of CA code over a hemisphere of the earth

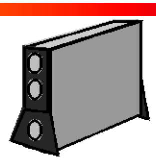
W/m^2 = 20 W/(2*PI*(6.371E6 m)^2) = 7.8E-14 W/m^2

- Effective collecting area of a gain=1 antenna follows G = 4*PI*Area/wavelength^2

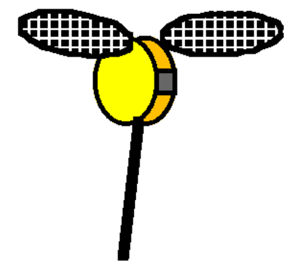
At L1 this area is A = (0.190 m)^2/(4*PI) = 2.9E-3 m^2

- Received signal C = 7.8E-14 W/m^2 * 2.9E-3 m^ = 2.3E-16 W -> -126 dBm
- Noise density @ 300 K is kT = -198.6 dBm/K/Hz + 24.8 dB-K = -173.8 dBm/Hz
- C/No = +47.8 dB-Hz, or SNRv (1 second) = 347
- Phase error in radians ~ 1/SNRv
- Phase error (1 sec) in meters ~ lambda/(2*PI*SNRv) ~ 190 mm/(2*PI*347) ~ 0.09 mm
- So, 0.1 mm baseline repeatability using 2 hr of data per day should be expected if the receiver properly designed. Our receivers are digital in the sense a computer is digital. We used to pretest by tracking same satellite through all channels and require measurements agree to the last digit.

Autonomy&Flexibility&Capability



GPS/MET



Status

- Pegasus Launch 4/3/95
- About one software version per month
- Receiver remains healthy after 27 months

TurboRogue Firsts

- First Occultation Measurements of Earth's atmosphere
- First true cold start of GPS receiver in orbit(4/12/95).
- First Autonomous Scheduling of Science Observations
- First single antenna GPS attitude determination

Problems (through 1st year on orbit)

- AS
- Data Outages

Many	Space Craft Resets
Many	Space Craft Power Problems
Many	Receiver Resets (SEU's)
Many	Communication Errors
10-20	Space Craft attitude problems -Single Antenna Attitude Determination
6-7	Commanding Errors
7	Uploads (1 lasting 90 minutes)
2	Software Errors

- 1 Latch-Up
  ~48 hour duration, affected only one channel,

Past JPL GNSS INSTRUMENT DELIVERIES: 1992-2000

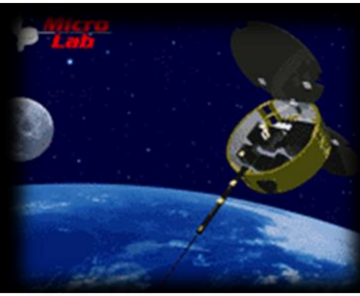
JPL/NASA GNSS Receivers: Past and Present
> 210 Flight-Years of Successful Operations in Space

The most precise GPS receivers flown in space -- enabling new science and navigation capabilities

TurboRogue
1992

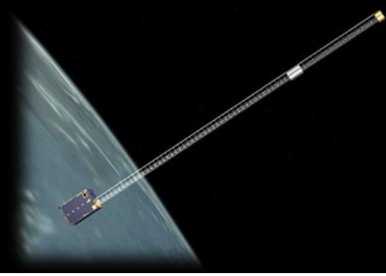
Commercial Ground Receiver

GPS/MET (Microlab-I)
Apr 1995



First GPS RO
Much on-orbit SW tuning

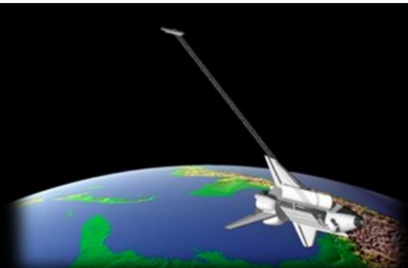
Ørsted
Feb 1999



~4 Watts

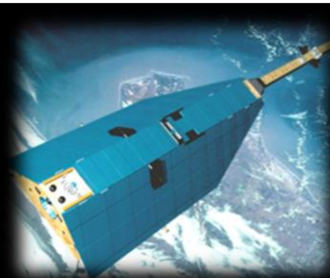
SUNSAT
Feb 1999

SRTM
Feb 2000



45-cm accuracy
Record shuttle accuracy

CHAMP
Jul 2000



4-cm RO Demo

SAC-C
Nov 2000

Sub-meter RT demo
First L2C track from space
First Open Loop tracking, reflections antenna, etc.

Past JPL GNSS INSTRUMENT DELIVERIES: 2001-2016

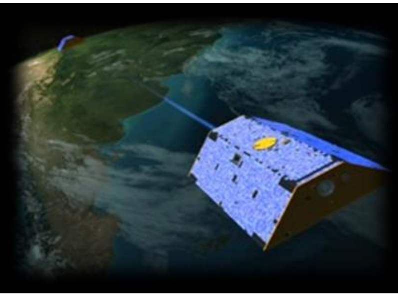
JPL/NASA GNSS Receivers: Past and Present
> 210 Flight-Years of Successful Operations in Space

The most precise GPS receivers flown in space -- enabling new science and navigation capabilities

JASON-1
Dec 2001

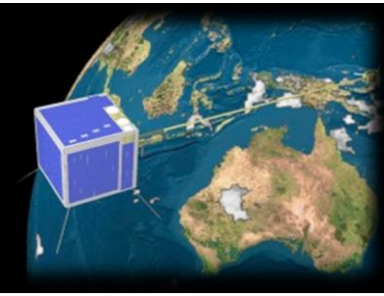
<1-cm radial accuracy

GRACE
Mar 2002



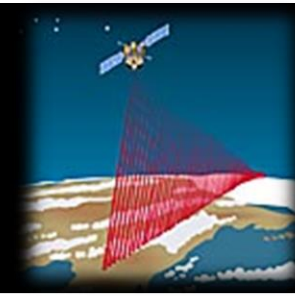
Sub micron ranging
RO, Star camera

FedSat
Dec 2002



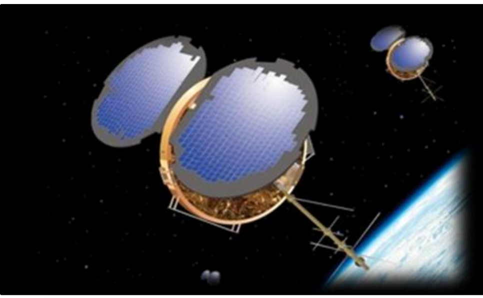
>25,000 power off/on cycles

ICESat
Dec 2002



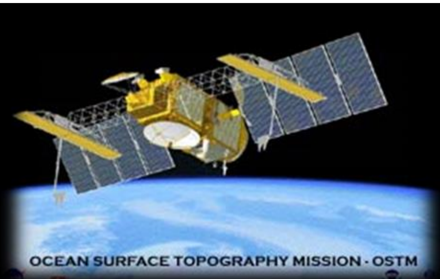
5-cm accuracy
Utilized as primary S/C nav

COSMIC
Apr 2006



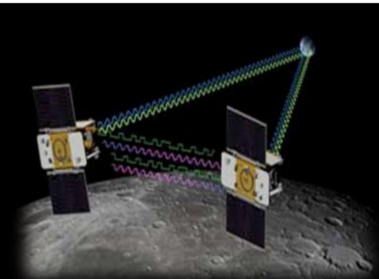
Six Sat Occultation Mission
First dedicated RO Constellation
4 dual-freq antennas

OSTM
Jun 2008



Exceeded Mission Life
Still going at ~43 kRAD TID

GRAIL
Sep 2011



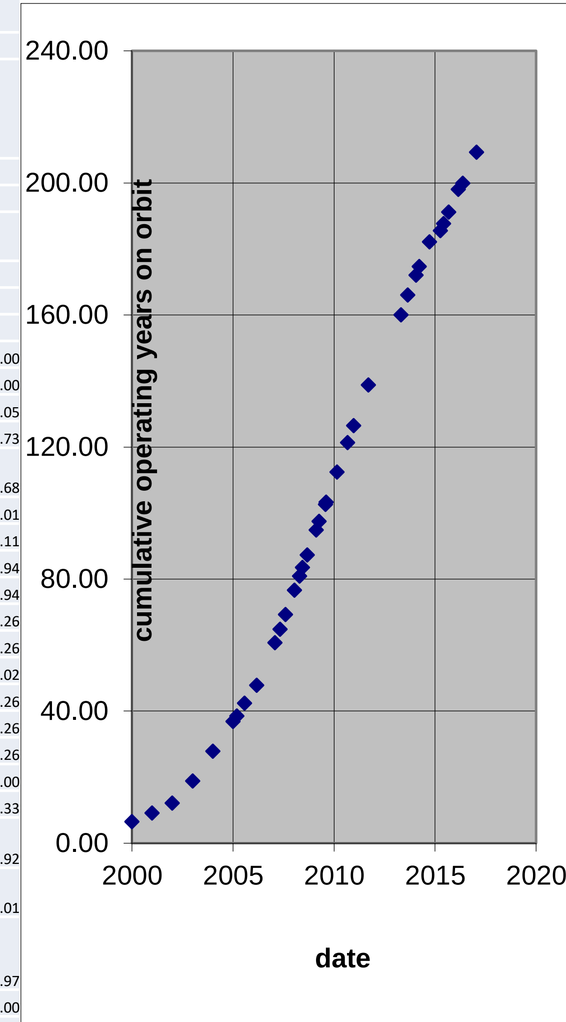
Lunar orbit
Ranging, data, &
time transfer w/o GPS

JASON-3
Jan 2016

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Summary of Past Missions

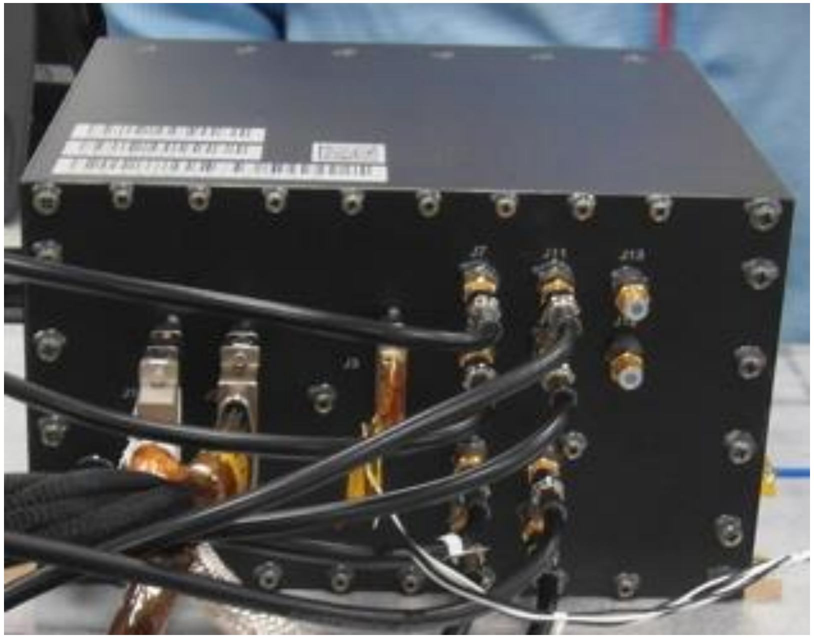
RECEIVER/MISSION	Prime country	LAUNCH				End of mission			EOM/today	years in orbit	orbit	dose rate	TID
blue=non-JPL		YR	MO	DAY	epoch	YR	MO	DAY	epoch		(km)	(kRAD/yr)	(kRAD)
TurboRogues									-0.086			2.5 mm al	
GPS/MET (expt end)	USA	1995	4	3	1995.3	2000	1	1	2000.000	4.745		~ actual shielding for Jason series	
Wakeshield I (expt end)	USA	1995	9	7	1995.7	1995	9	17	1995.711	0.027			
Wakeshield II (expt end)	USA	1996	11	1	1996.8	1996	11	11	1996.861	0.027			
Ørsted still going in 2014 but funding stopped	DENMARK	1999	2	23	1999.1	2014	11	15	2014.872	15.728			
IOX (PicoSat-9) AEROSPACE MISSION	USA	2001	8	31	2001.7				2017.070	15.405			
SunSat (satelllite failed)	U S AFRICA	1999	2	23	1999.1	2001	1	19	2001.049	1.906			
BlackJacks													
SRTM rcvr1	USA	2000	2	11	2000.1	2000	2	21	2000.138	0.027	233	0.10	0.00
SRTM rcvr2	USA	2000	2	11	2000.1	2000	2	21	2000.138	0.027	233	0.10	0.00
CHAMP (re entry)	GERMANY	2000	7	15	2000.5	2010	9	19	2010.716	10.178	460	0.30	3.05
SAC-C lost sat contact	ARGENTINA	2000	11	21	2000.9	2013	8	15	2013.622	12.734	700	1.00	12.73
JASON* failed at high TID, 37 kRAD	FRANCE/USA	2001	12	7	2001.9	2009	4	8	2009.269	7.336	1,336	5.00	36.68
FedSat** sat batt failed	AUSTRALIA	2002	12	14	2003.0	2007	5	1	2007.333	4.381	811	1.60	7.01
ICESat-sat re-entry	USA	2003	1	12	2003.0	2010	8	30	2010.663	7.633	600	0.80	6.11
GRACE1	GERMANY	2002	3	17	2002.2				2017.070	14.860	498	0.40	5.94
GRACE2	GERMANY	2002	3	17	2002.2				2017.070	14.860	498	0.40	5.94
COSMIC1	TAIWAN/USA	2006	4	14	2006.3				2017.070	10.785	785	1.60	17.26
COSMIC2	TAIWAN/USA	2006	4	14	2006.3				2017.070	10.785	785	1.60	17.26
COSMIC3 lost sat comm, IGOR OK	TAIWAN/USA	2006	4	14	2006.3	2010	8	1	2010.583	4.298	711	1.40	6.02
COSMIC4	TAIWAN/USA	2006	4	14	2006.3				2017.070	10.785	785	1.60	17.26
COSMIC5	TAIWAN/USA	2006	4	14	2006.3				2017.070	10.785	785	1.60	17.26
COSMIC6	TAIWAN/USA	2006	4	14	2006.3				2017.070	10.785	785	1.60	17.26
Roadrunner/TACSAT-2	USA	2006	12	16	2007.0	2007	12		2007.914	0.956			0.00
TerraSAR-X (GAC/EADS/infoTerra)	GERMANY	2007	6	15	2007.5				2017.070	9.615	514	0.45	4.33
CNoFs (CORISS Aerospace mission, Spectrum Astro rcvr)	USA	2008	4	16	2008.3				2017.070	8.779	850	1.70	14.92
JASON-2/OSTM FM-A XXX -> FM-B (Aug 2014)	FRANCE/USA	2008	6	20	2008.5				2017.070	8.602	1,336	5.00	43.01
Tandem-X (Mar 2015 problem with low L2 SNR causing loss of data, see from both POD antennas)	Germany	2010	6	21	2010.5				2017.070	6.599	514	0.45	2.97
GRAIL1 lunar orbit, impact	USA	2011	9	10	2011.7	2012	12	17	2012.961	1.269			0.00
GRAIL2 lunar orbit, impact	USA	2011	9	10	2011.7	2012	12	17	2012.961	1.269			0.00
KompsSat-5	Korea	2013	8	22	2013.6				2017.070	3.430	685	1.00	3.43
EQUARS (RO & ion)	Brazil												
JASON-3***	FRANCE/USA	2016	1	17	2016.0				2017.070	1.027	1,336	5.00	5.13
PAZ (IGOR+) H&V RO and rain drops	Spain	2017?											
										209.642	years on on-orbit, all receivers		

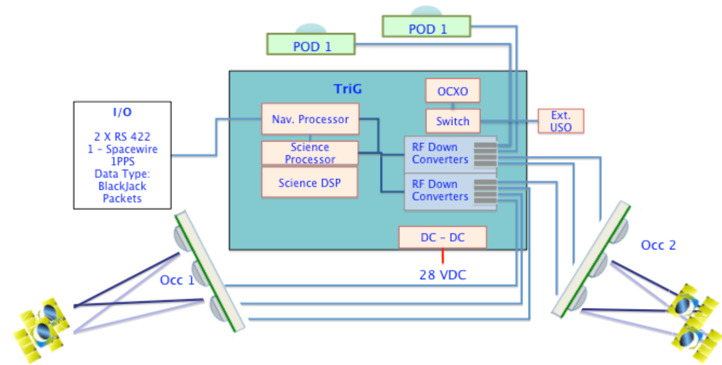


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Present: TRIG RECEIVER

- NASA funded space flight GNSS, fully reconfigurable science and navigation sensors
- State of the Art Radio Occultation (RO) capabilities.
- Increased RO profile count, higher data quality, lower altitudes (relative to COSMIC-1 receiver)
- Linux based Science Processor designed to extract highly dynamic, very faint (MSR demo to +17 dB-Hz), GNSS signals

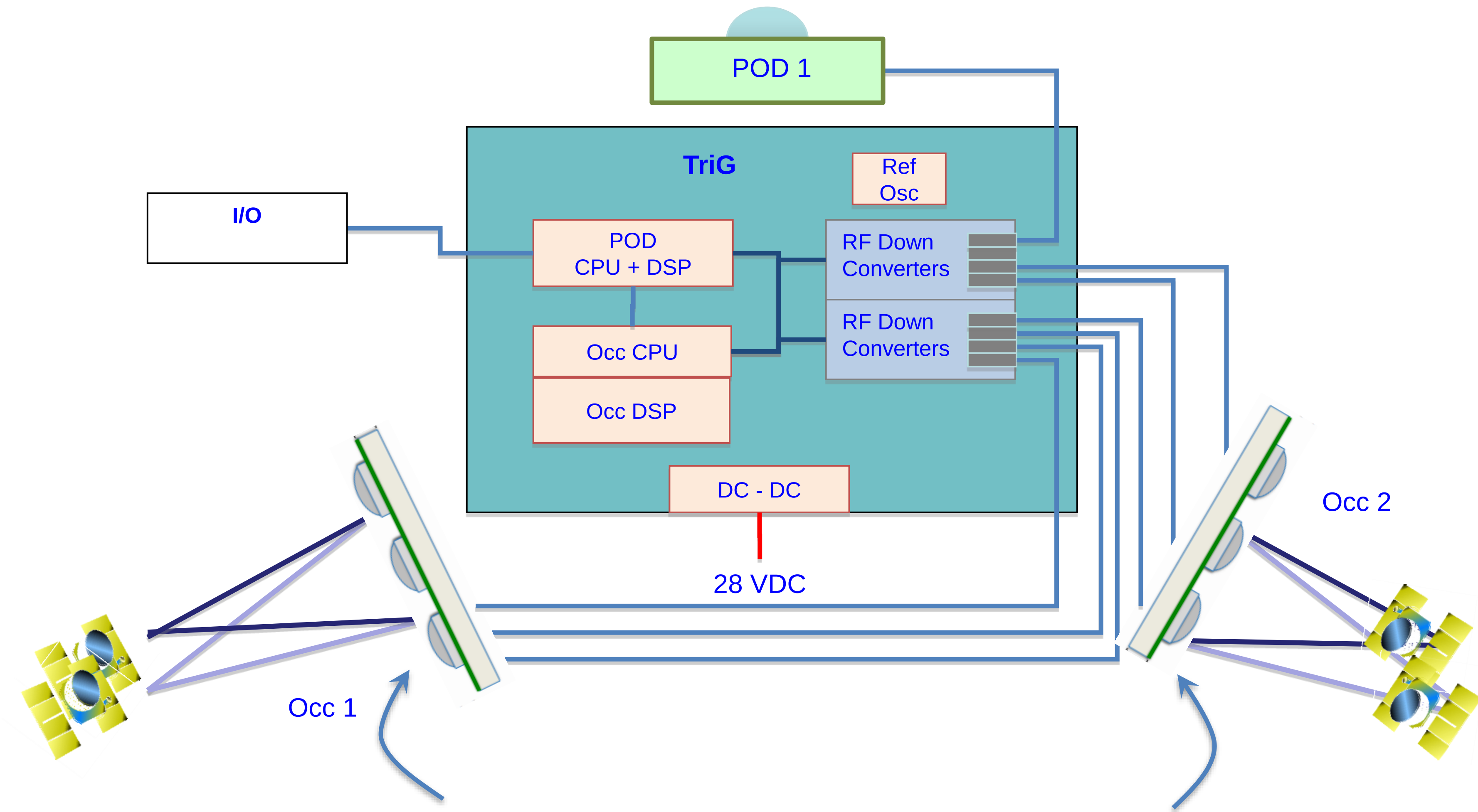




Key Features:

- Simultaneous tracking of up to:
  - 16 satellites for POD (dual frequency)
  - 6 satellites for RO (dual frequency)
- Up to 16 antenna inputs
- Supports in-flight software & firmware uploads
- Digital beam steering
  - High gain, multiple simultaneous beams
- Excellent Clock - Internal OCXO: 4E-13 (1 sec)
- High Rel / Rad Hard - 40 krad TID
- Compatible with all legacy and future GNSS L-band signals: e.g. GPS L1C/L1CA, L2P/L2C, L5, Galileo E1, E5a, GLONASS CDMA, GLONASS FDMA, BeiDou, plus DORIS ground beacons at UHF and S-band

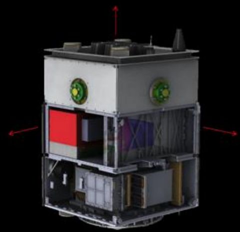
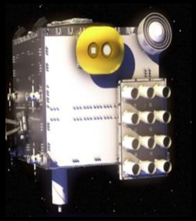
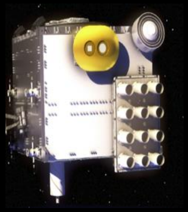
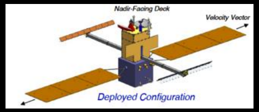
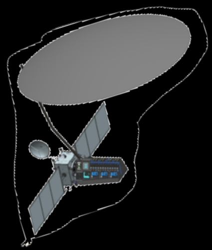
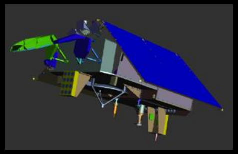
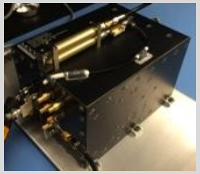
Present JPL TRIG RECEIVER: BLOCK DIAGRAM



12 Element Occultation Antennas Arrays
(Support azimuth steering across Earth limb)

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

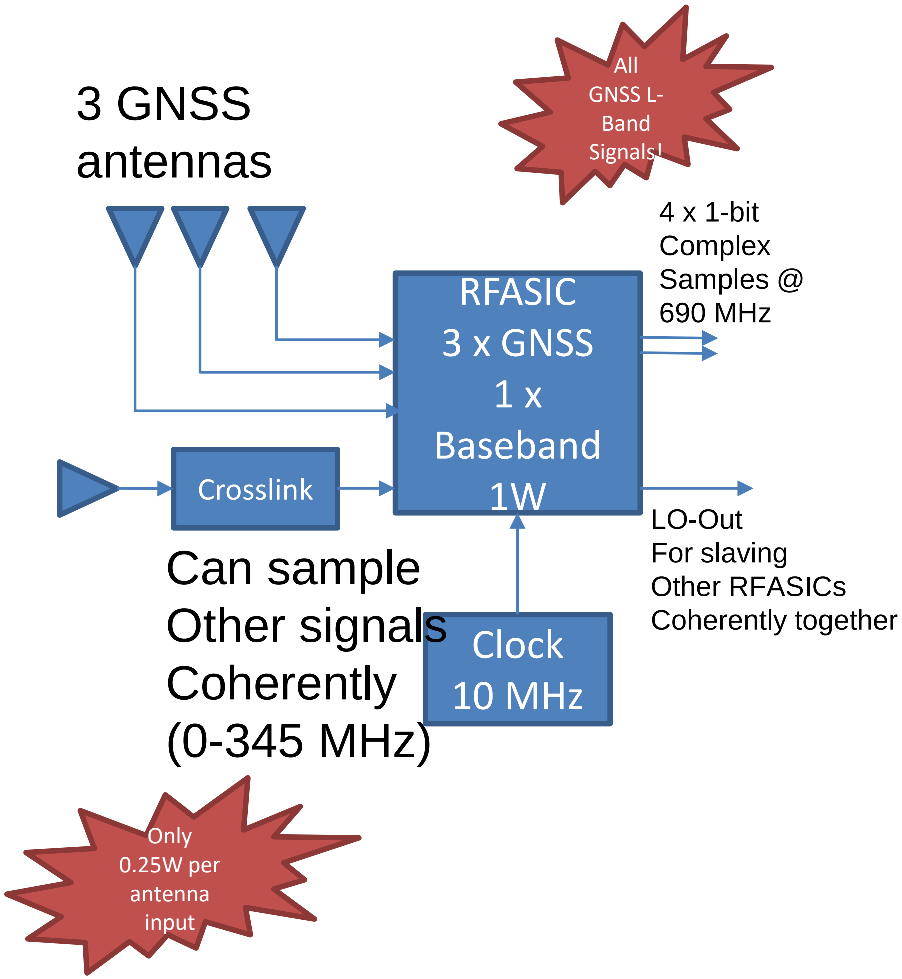
"Present" TRIG MISSIONS

	DSAC	COSMIC 2 Equatorial	GRACE FO	COSMIC 2 Polar	SWOT	Ni-SAR	JASON CS/Sentinal-6
							
TriG Payload Type							
Description	Precise Clock Validation Timing using Precise Orbit Determination	Radio Occultation and Space Weather Observations.	Micron Ranging and Precise Orbit Determination Some RO	Radio Occultation and Space Weather Observations	Precise Orbit Determination 1553 comm card	Precise Orbit Determination Cold Spare	Precise Orbit Determination Radio Occultation 1553 comm card
Mission Phase	Phase C/D	Phase C/D	Phase C/D	Phase A	Phase A	Phase A	Pre Phase A
Launch	Sep 2017	Sep 2017	Jan 2018	2020	2020	2022	2020 and 2026
System Mass (kg) CBE	6	12	6	12	6	6	22
Power Est (W)	25	65	25	65	35	30	65

Future Technology and Mission Developments

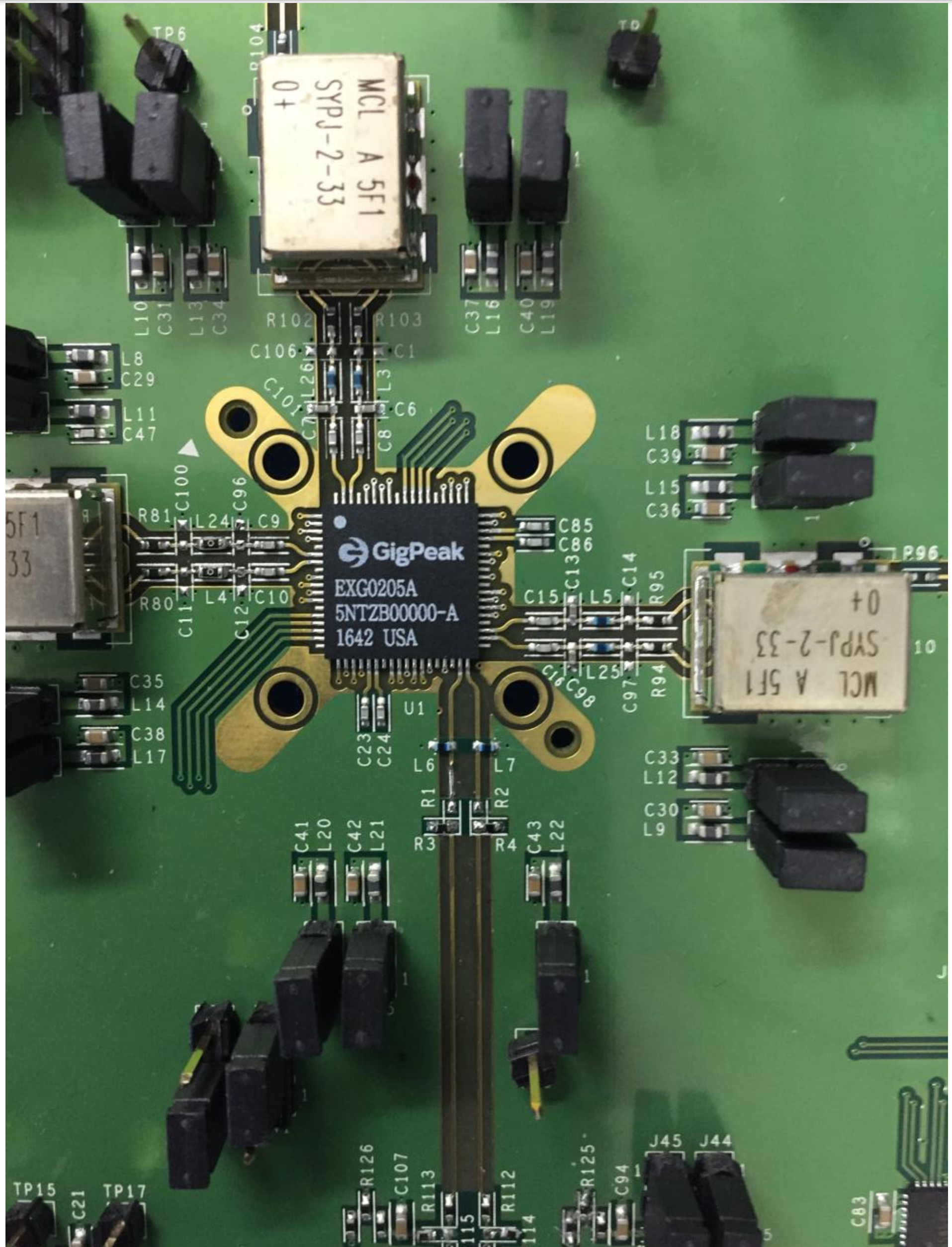
- Digital RFASIC
  - Higher performance from greater bandwidth
  - Lower power per antenna enables larger antenna arrays
- RO links between spacecraft at other planets
- Integrated GNSS + Inter-satellite range & telemetry is being developed
- RO and POD on cubesats
- Enhanced use of GNSS and SoO surface reflections using high-performance receiver
- Galileo signal tracking has been demonstrated off line, and will be implemented into the Trig as needed
- Beidou, IRNSS, and QZSS, etc, will be developed and implemented as needed
- Tracking at DORIS frequencies has been demonstrated using modified Trig hardware, software will be developed and implemented as needed

RF ASIC



- **Radiation hardened** GNSS RF ASIC (RF-to-bits)
- 4 inputs per chip
  - **3x L-Band** (1150-1610 MHz)
  - 1x Baseband (0-350 MHz)
- 1 W per RFASIC (total power)
- Runs off standard **10 MHz reference oscillator**
- **Can slave N of these chips together** for 3*N phased array applications. Slaves run at 0.75W per 3 antennas.
- Each chip **replaces about 24 MAX2112s** and does this for 1/10th of the power.

RFASIC in JPL's 138 GNSS Lab

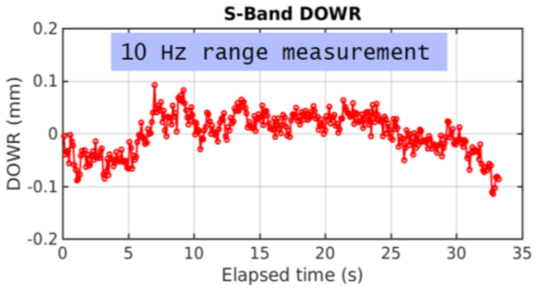


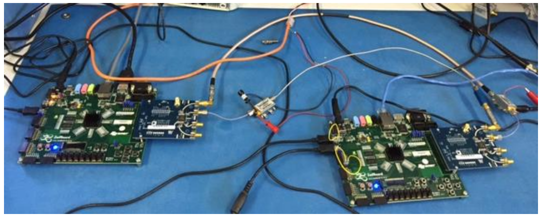
mm Level Small-Satellite Formation Control

- The goal is to enable distributed spacecraft/sensors to mm-level precision over numerous years with ultra fuel-efficiency, using GPS receivers with integrated dual-frequency cross links.
- As Earth remote sensing instruments and techniques advance there are applications that require **coordinated observations and distributed sensing** among multiple satellites. These Future Earth science missions will require precise knowledge of the relative positions and clock offsets between satellites as well as efficient long-term formation control. Precise knowledge of the relative positions to sub-millimeter and clock offsets to tens of picoseconds are envisioned.

- Three COTS Transceiver modules have been tested, at frequencies from 2 to 60 GHz.
- These will be used at dual frequencies to transfer data and provide precision constellation figure and time transfer.
- The plots to the right show 10 Hz range measurements with ~0.03 mm precision

- The measurement technology and control algorithm development and test work is ongoing.





JPL GNSS INSTRUMENT SUMMARY

- JPL has successfully delivered 28 flight GNSS instruments for operation in space
    - Over 210 instrument-years of successful on-orbit performance
- JPL instruments have successfully generated best-in-class, operational precise orbits and GNSS RO measurements
- JPL is continuing to innovate and improve the capabilities of flight GNSS instruments
    - The TriG – highly reconfigurable GNSS science instrument
    - Digitally steered high gain antenna arrays
    - Low-power RO instruments for Cubesats
    - Formation flying including telemetry cross links
- JPL technology and expertise is available to U.S. commercial entities
    - Technology transfer and licensing
    - NASA Space Act Agreements

- BACKUP VGs FOLLOW

COSMIC-1 MISSION OVERVIEW

- Launched in April 2006, US (NSF)/Taiwan Collaboration, US activities managed by NSF/UCAR/JPL
- $100M project – 6 Orbital microsatellites designed for 5 years of operations
- Produced 1800-2500 worldwide all weather soundings per day
- Produced high accuracy temperature profiles
- Data incorporated into NOAA operational forecasting as of May 2007
- Generated significant positive impacts on weather forecasting
- Now well past design life; Reduced capability (due to failures in satellite components)

Cosmic 1: Single spacecraft assembly

Cosmic 1 spacecraft stack-up